ARMY RESEARCH LABORATORY

Experimental Demonstration of a 120-mm Ram Accelerator

D. L. Kruczynski
A. W. Horst
T. C. Minor

ARL-TR-1237

November 1996

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1996

3. REPORT TYPE AND DATES COVERED
Final, February 1992 - October 1992

4. TITLE AND SUBTITLE
Experimental Demonstration of a 120-mm Ram Accelerator

5. FUNDING NUMBERS
PR: 1L162618AH80

6. AUTHOR(S)
D. L. Kruczynski, A. W. Horst, and T. C. Minor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WT-PA
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-1237

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Ram acceleration is an emerging propulsion technology in which a projectile similar in shape to the centerbody of a ramjet aircraft engine is injected at high speed into a tube filled with a combustible gaseous mixture. As the projectile moves into the tube, under supersonic conditions, shocks occur on and around the projectile. If the gases are then ignited, either by the energy in the shock system or an external mechanism, the combustion around or behind the projectile can be self-sustaining. The net effect is to generate a localized high-pressure region around and/or behind the projectile which produces acceleration. Work at the University of Washington, Seattle, has demonstrated velocities in excess of 2.6 km/s in 38-mm caliber, while theory predicts velocities above 7 km/s may be obtainable.

The first successful ram acceleration experiment at 120-mm caliber is presented. Performance at this larger caliber was as predicted from scaling considerations. Reported experiments have shown that propellant mixing by partial pressure is a viable alternative to more complex mixing schemes for obtaining homogeneous propellant mixtures in ram accelerators. The usefulness of inert firings to analyze obturator performance and shock/pressure structure in ram accelerators has been further validated. Finally, the scaling potential of ram acceleration has been firmly established with the first successful test at 120-mm caliber.

14. SUBJECT TERMS
ram acclerator, hypervelocity gun, subsonic combustion, high-pressure combustion

15. NUMBER OF PAGES
25

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

INTENTIONALLY LEFT BLANK.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Michael Nusca for critical insights provided by his companion CFD research; Messrs. Robert Hall, James Bowen, John Hewitt, James Tuerk, Dennis Meier, Joseph Colburn, Arthur Koszoru, and Carl Ruth for continued experimental support; Mr. Maher Kiwan and Dr. Federico Liberatore for engineering, analytical, and experimental support; and Dr. Carl Knowlen and Professor Adam Bruckner for numerous technical insights.

INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK.

LIST OF FIGURES

INTENTIONALLY LEFT BLANK.

LIST OF TABLES

INTENTIONALLY LEFT BLANK.

1. INTRODUCTION

The Weapons Technology Directorate of the U.S. Army Research Laboratory (ARL) (formerly the U.S. Army Ballistic Research Laboratory [BRL]*) has been conducting an experimental and computational effort aimed at developing sufficient understanding of the ram acceleration process to successfully scale the process to larger caliber guns and launch masses. This report presents the first results from the experimental scaling effort with a 120-mm ram accelerator. Scaling discussions based on data from three bore diameter accelerators are presented. Additional background on the ARL ram accelerator can be found in Kruczynski (1991a, 1991b, 1992) and Nusca (1991a, 1991b).

2. PROJECTILE, FACILITY, AND INSTRUMENTATION

The ARL ram accelerator program has been dubbed HIRAM or Hybrid Inbore Ram accelerator for its use of combined propulsion technologies (conventional solid propellant projectile launch followed by ram acceleration). The current projectile design is a geometric scale-up of one of the most extensively tested designs of the University of Washington (UW). The basic projectile is shown in Figure 1. Currently, the projectile is made from a high-strength aluminum alloy (7075-T6) and has a mass of 4.29 kg.

The accelerator tubes are made from retired 120-mm M256 tank guns appropriately machined and mated. Transition from the conventional solid propellant launcher to the ram accelerator is made through a transition/vent section. This section serves the dual purpose of decoupling the conventional launch gun from the ram accelerator (through a sliding interface) and venting the backpressure from the conventional charge combustion, which further assists in decoupling the two processes. The HIRAM facility was initially designed to accommodate five 4.7-m-long accelerator tubes for a total combined acceleration of 23.5 m. There is also allowance for future expansion to 60 m. Initial experiments reported here were performed using a single 4.7-m accelerator section. Gases are supplied from a bottle farm and diaphragm compressor capable of supplying gases at pressures up to 35 MPa (5,000 psi). All gas supply operations are handled remotely using solenoid-controlled, air-operated valves. A large vacuum pump is also installed near the accelerator to evacuate any part (or all) of the launch/vent/accelerator sections, when desired. Figure 2 shows a drawing of the primary facility.

* The U.S. Army Ballistic Research Laboratory (BRL) was deactivated on 30 September 1992 and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

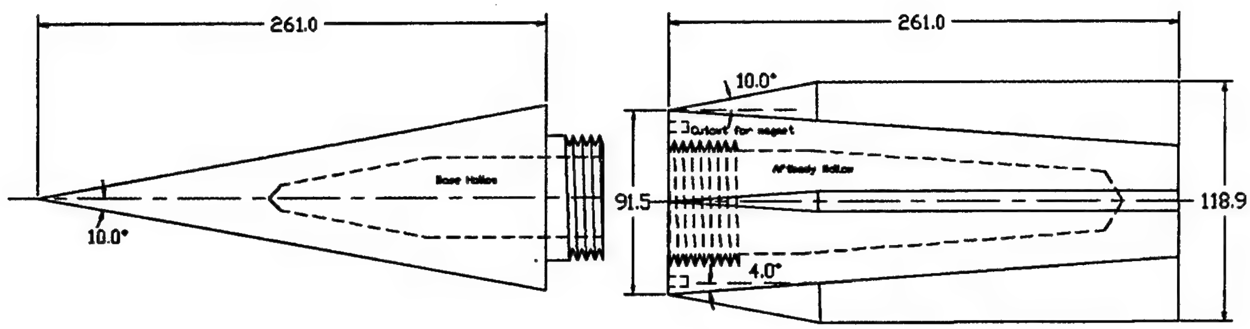

Figure 1. The 120-mm HIRAM projectile.

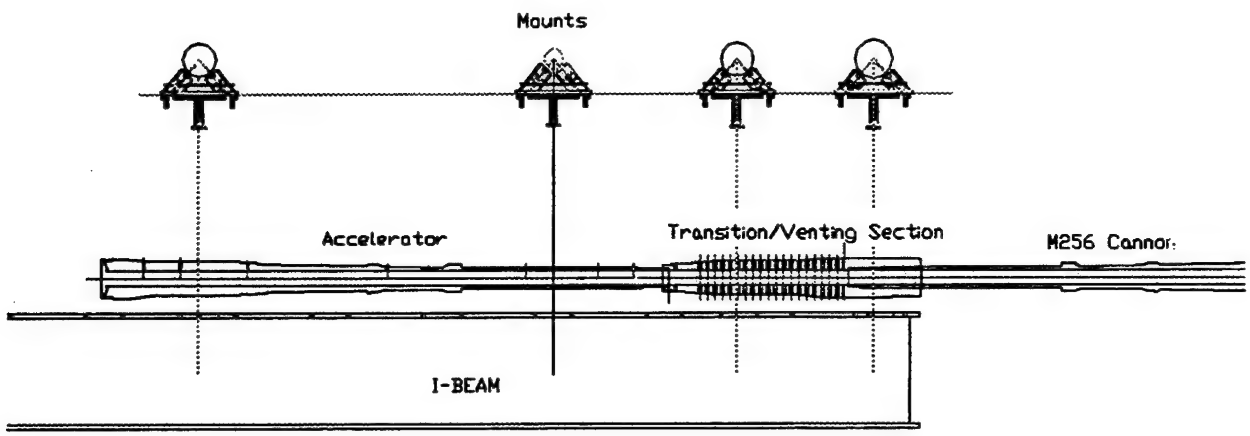

Figure 2. Primary HIRAM accelerator components.

Instrumentation within the accelerator tube and diagnostics available during HIRAM firings include tube wall-mounted quartz pressure transducers, photodiode light detectors, and electromagnetic sensors. In addition, high-speed movie and still-capture (smear) cameras are employed at various locations around the accelerator during firings. Samples of propellant mixes for later analysis may be taken (remotely) after filling the accelerator. Doppler radar, magnetic coils, and electro-optical sensor devices (sky screens) are used to measure projectile velocity after exiting the accelerator.

3. SCALING EFFECTS

3.1 Propellant Ignition and Induction Times. Early data from firings at the UW (Hertzberg, Bruckner, and Bogdanoff 1988; Bruckner et al. 1991; Knowlen, Bruckner, and Hertzberg 1992; Knowlen et al. 1992), the Institut Saint Louis in France (Giraud et al. 1992; Giraud, Legendre, and Simon 1992), and ARL indicated that geometric scaling required changes in propellant chemistry. At the time, it was thought that a relationship between geometry and combustion induction times existed (Kruczynski 1992). The relationship was thought to be such that for the same given propellant mixtures at the same pressures and with similar projectile entrance velocities, the onset of significant energy release will take place in similar timeframes. Thus, energy release that occurred on the afterbody of a smaller scale projectile may occur on the nose of a larger (and longer) scale projectile. Thus, these early experimental findings had prompted researchers to lower propellant ignition sensitivity as calibers increased as shown in Table 1.

Table 1. Typical Propellants for Several Ram Accelerators in Early Experiments

System Caliber (mm)	Propellant Mixture (typical)	Speed of Sound (m/s)	CJ* Velocity (m/s)	$\frac{Q}{C_p \Delta T}$ at Mach # = 3
38	$2.4CH_4 + 2O_2 + 5.8N_2$	363	1,700	5.01
90	$3CH_4 + 2O_2 + 7N_2$	364	1,574	4.39
120	$3CH_4 + 2O_2 + 10N_2$	361	1,448	3.72

Very recent experiments in the ARL 120-mm ram accelerator have revealed that large-caliber accelerators can operate at propellant energy levels equal to those of smaller caliber accelerators. These results will be reported in a future ARL report.

3.2 Propellant Charge Pressure. To date there have been limited data (see Figure 3) indicating that precharge pressures are related to combustion pressures around the projectile. That is, for higher propellant precharge pressures, higher combustion pressures and thrust are produced. However, these studies have been limited to precharge pressures of 5 MPa (750 psi). It remains to be seen if this trend

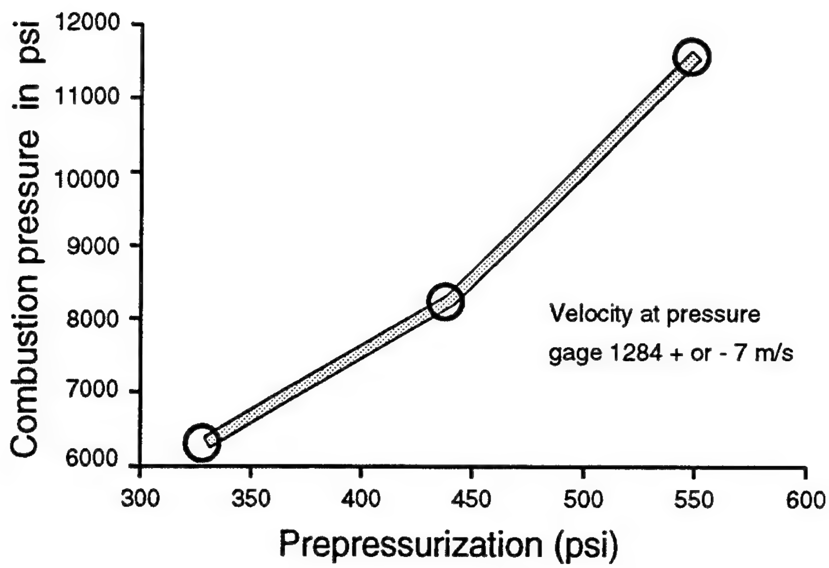

Figure 3. Combustion pressure vs. precharge pressure.

will continue at higher pressures. One possibility is that higher pressures will reduce reaction induction times so that progressively less ignitable (cooler) mixtures will be required to preclude premature energy release. The ARL HIRAM facility is the first ram accelerator capable of operation at significantly higher propellant precharge pressures, up to at least 10 MPa (1,500 psi), and we will evaluate this important parameter early in the research program (this has been done and will be reported separately).

4. FIRST EXPERIMENTAL RESULTS IN A 120-mm RAM ACCELERATOR

4.1 Propellant Mixing. The HIRAM system is the first ram accelerator to employ the relatively simple technique of partial pressure mixing to achieve desired propellant component ratios. As such, there was some concern about the ability to obtain accurate and homogeneous mixtures when the gases are injected separately into a ram accelerator. Table 2 presents results from two full-scale mixing tests in the first stage of the HIRAM accelerator, as well as from the first "live" propellant firing. In the HIRAM system, the gases are injected to promote mixing at three locations—one at each end and one in the center of each accelerator tube. Sampling or venting is done at a separate port located 0.405 m to the side of the center fill port. The data from the gas analysis reveal that the relative amount of each propellant component is reasonably close to that desired. However, since the mixtures were analyzed many hours after sampling, the homogeneity of the mixture at fill time is not assured (final mixing may be occurring in the sample bottle). Future efforts will be designed to analyze the mixtures within minutes of firing to further check the state of the tested gases.

Table 2. Partial Pressure Filling Analysis

Desired molar mixture ratio mixture and total pressure: $2O_2 + 10N_2 + 3CH_4$ at 51 atm (70 psi).						
Calculated/Experimental					Gas Chromatography (GC)	
Test No.	Gas[a]	Partial Pressure (psi)	Total Pressure (psi)	Volume Percent	Volume Percent (Concentration)	Percent Difference From Experimental
A[b]	Oxygen Nitrogen Methane	90 480 170	90 570 740	12.848 65.657 21.496	12.472 67.213 21.997	2.9 2.3 2.3
Implied molar mixture from CG: $1.8O_2 + 9.9N_2 + 3.3CH_4$						
B[c]	Oxygen Nitrogen Methane	100 490 160	100 590 750	13.179 66.425 20.392	14.010 66.987 20.649	5.9 0.8 1.2
C[d]	Oxygen Nitrogen Methane	100 490 160	100 590 750	13.179 66.425 20.392	13.300 70.000 18.000	0.9 5.1 11.7
Implied molar mixture from CG: $2.0O_2 + 10.5N_2 + 2.7CH_4$						

[a] Gases are listed in order of fill.

[b] Test No. A - Partial pressures from nonideal equation of state. Time from completion of chamber filling to withdrawal of sample was 2.5 min. The sample was analyzed within 45 min of being taken and again 18 hr later with essentially the same results. All sample (A and B) analyses were verified by duplicate testing.

[c] Test No. B - Partial pressures from ideal equation of state. A sample was taken 2 min after completion of chamber filling and analyzed 15 hr later.

[d] Test No. C - First live gas accelerator test (round 15). Partial pressures are from ideal equation of state. A sample was taken 1 min after filling and analyzed 19 hr later. Round 15 was fired immediately after taking the sample.

NOTE: The following are acknowledged sources of error:

- Partial pressures are rounded to the nearest 10-psi increment in these tests.
- No adjustment was made to allow for the volume of gas which gets trapped in the supply lines and is subsequently pumped into the chamber with the next gas (e.g., the nitrogen pushes in additional oxygen, while the methane pushes in additional nitrogen).
- The total error associated with sample preparation and CG analysis is ±2%.

4.2 Inert Gas Firings. Ram accelerators are unique for "gun like" systems in that the ignition and proper starting sequences can be studied in inert gases with reasonable expectation that this knowledge can be directly applied to "live" gas tests. A detailed study of these inert gas phenomena is given in Kruczynski and Nusca (1992). For brief comparative purposes, a tube wall pressure profile from an "unstarted" HIRAM projectile test sequence using inert gas (nitrogen) is shown in Figure 4. Note that shortly after entrance in the ram accelerator, the projectile is pushing a significant pressure wave ahead of itself. In combustible gas mixtures, these pressure waves would most likely produce combustion and higher leading pressures. Contrast the pressure profile of Figure 4 with that in Figure 5 of a properly started and running projectile in inert gas. Note that the projectile has little lead pressure activity and can clearly be seen separating from its obturator as noted by the low pressures between the projectile and the trailing obturator. Obtaining such cold starts is crucial to proper obturator development and eventual startup and acceleration in live propellants.

4.3 "Live" Gas Firings. Following a series of 14 shots through inert gases to characterize obturator performance and shock structure, the first firing of the HIRAM system with live gases was conducted. The propellant mixture used has been previously described in Tables 1 and 2. The projectile was injected into the HIRAM accelerator (4.7 m long) at 1,170 m/s from a conventional solid propellant gun (Kruczynski 1991b). Proper ignition and subsequent acceleration were achieved. Figures 6–11 show a series of pressure profiles as the projectile moved through the accelerator. These pressure profiles indicate that ram combustion occurred almost immediately upon entry into the accelerator and this combustion produced high pressures immediately behind the projectile throughout the accelerator. The velocity profile appears in Figure 12. The projectile accelerated from its entrance velocity of 1,170 m/s (Mach 3.2) to 1,419 m/s (Mach 3.9), which is just under the Chapman-Jouget (C-J) detonation speed (1,448 m/s) for this mixture. The projectile appeared to accelerate more quickly as it proceeded downtube and left the accelerator with full-ram combustion established as verified by high-speed photography. The velocity gain by the projectile matched predicted values based on scaled UW data.

5. SUMMARY

The first successful ram acceleration experiment at 120-mm caliber was conducted. Performance at this larger caliber was as predicted from scaling considerations. Reported experiments have shown that

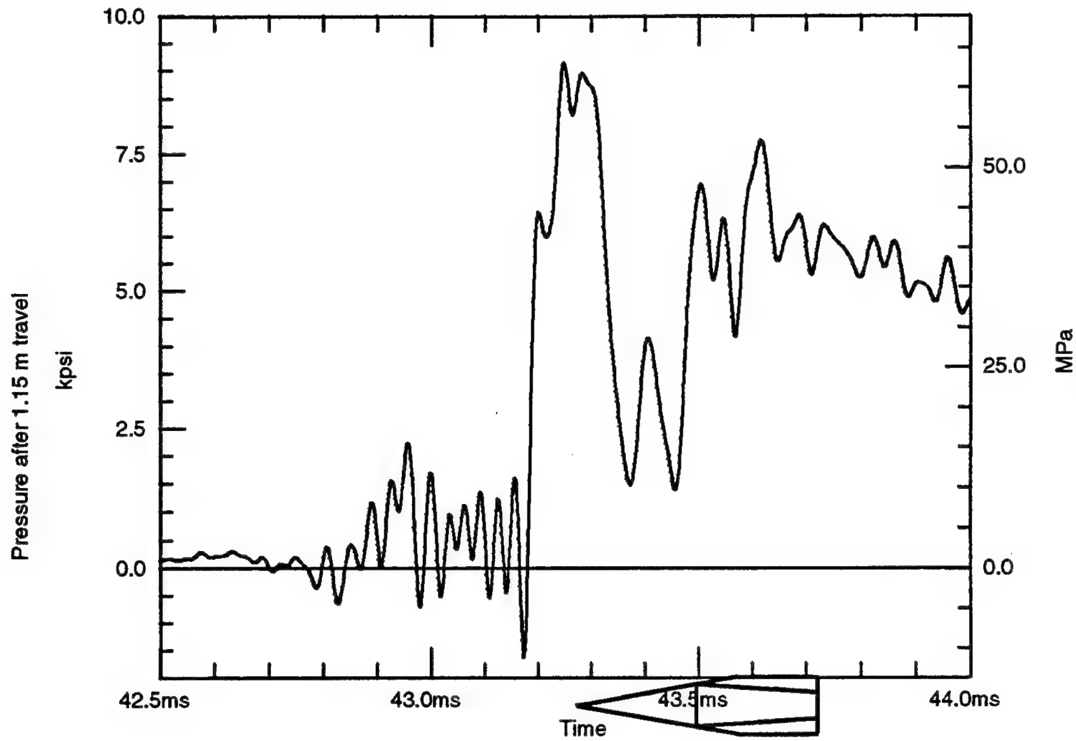

Figure 4. "Unstarted" projectile using inert gas (nitrogen). Note significant pressure wave activity in front of the projectile. Projectile is scaled to local velocity.

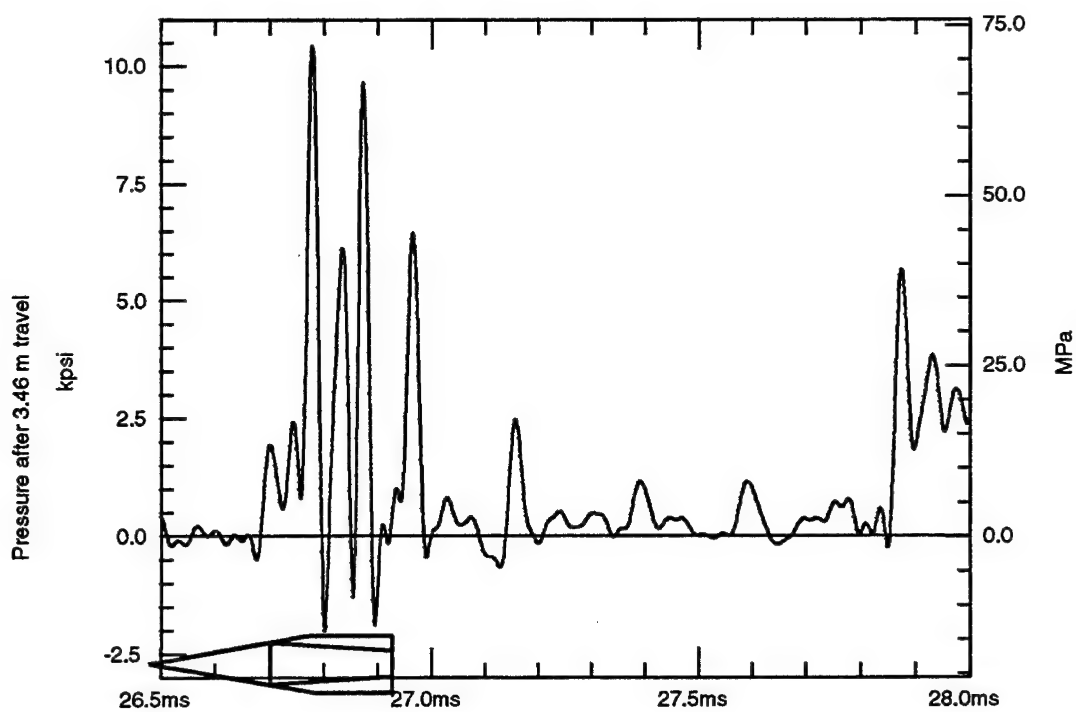

Figure 5. "Started" projectile using inert gas (nitrogen). Note little pressure wave activity in front of the projectile. Projectile is scaled to local velocity.

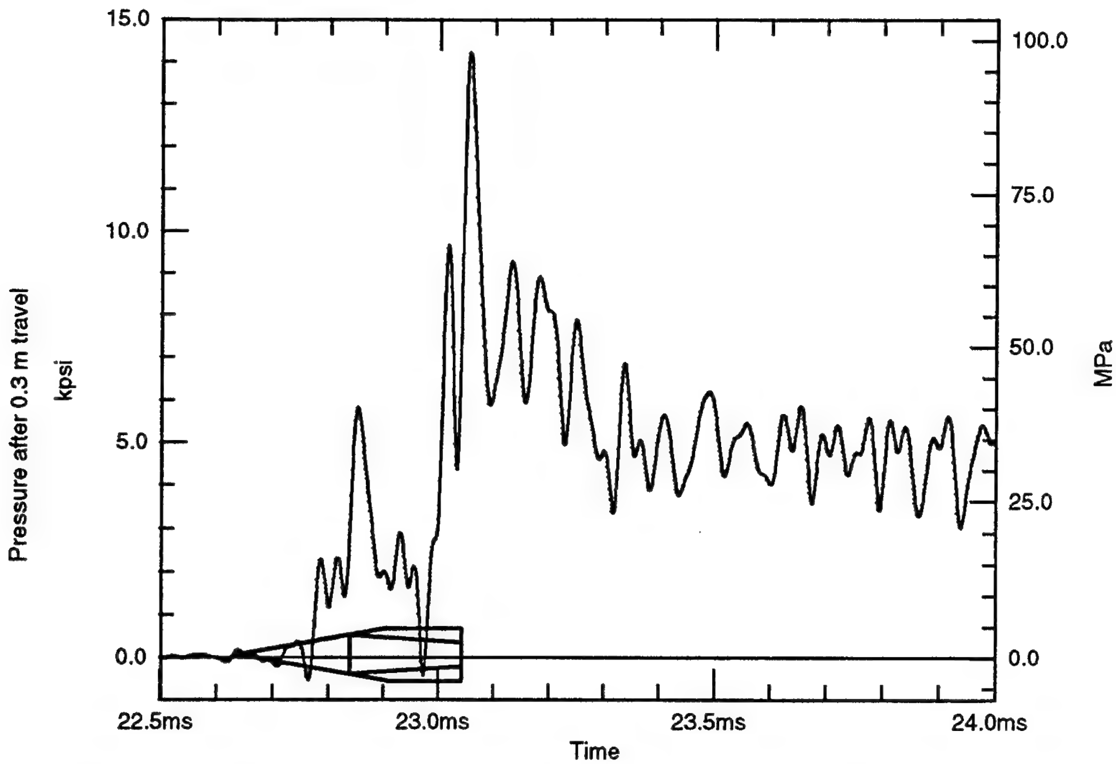

Figure 6. Ram combustion in a 120-mm accelerator after 0.3-m travel. Note high levels of pressure immediately behind the projectile indicating combustion (compare with Figure 5 with inert gas). Projectile is scaled to local velocity.

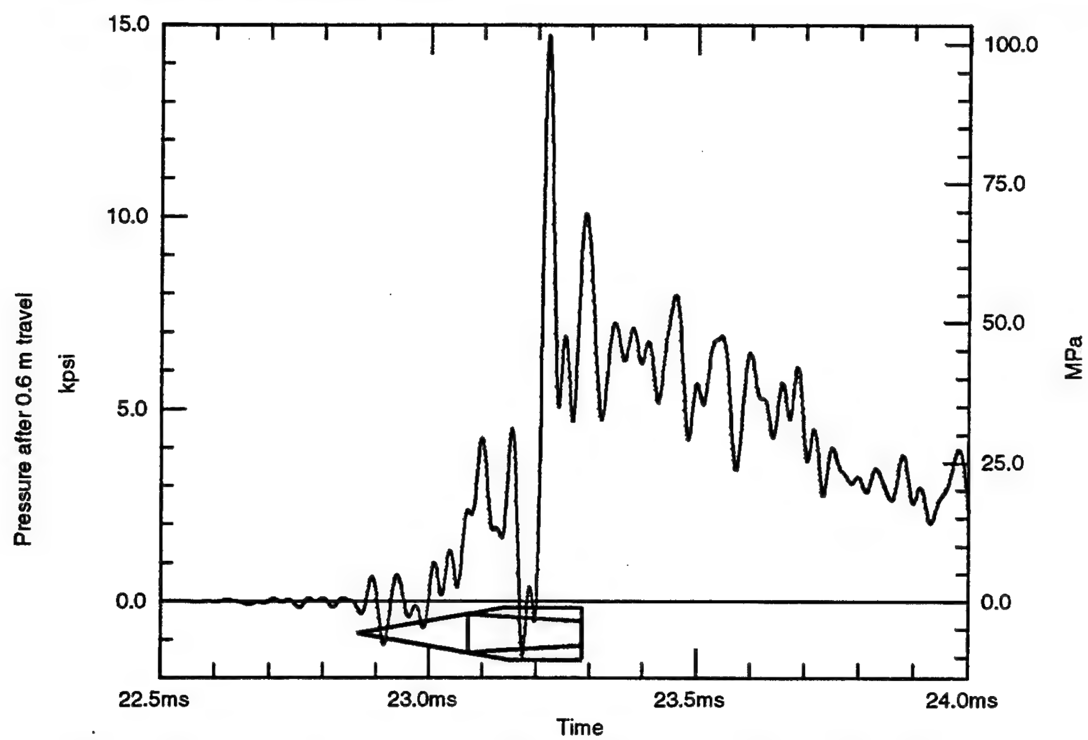

Figure 7. Ram combustion in a 120-mm accelerator after 0.6-m travel. Projectile is scaled to local velocity.

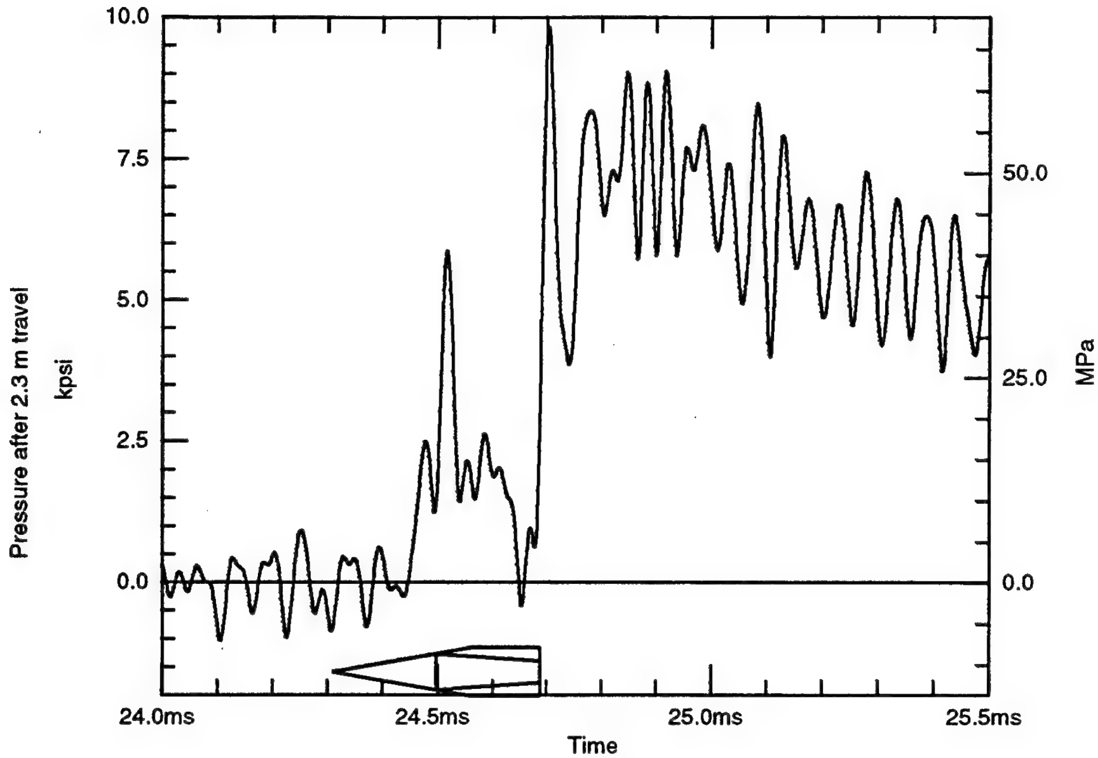

Figure 8. Ram combustion in a 120-mm accelerator after 2.3-m travel. Projectile is scaled to local velocity.

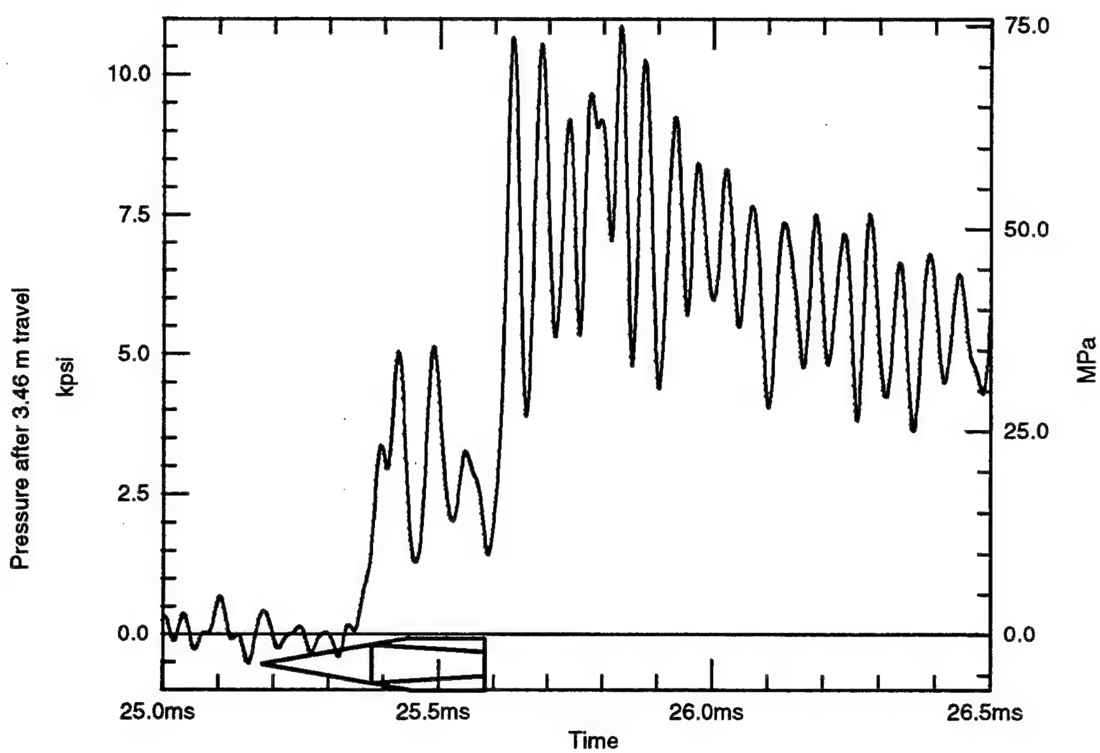

Figure 9. Ram combustion in a 120-mm accelerator after 3.46-m travel. Projectile is scaled to local velocity.

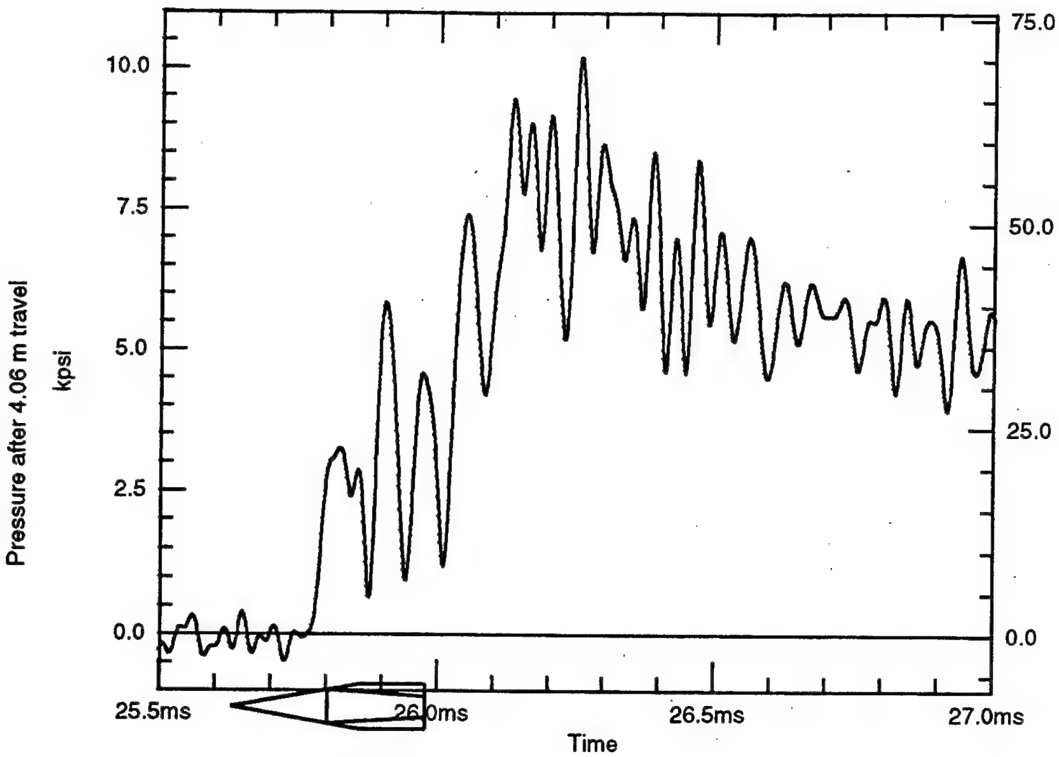

Figure 10. Ram combustion in a 120-mm accelerator after 4.06-m travel. Projectile is scaled to local velocity.

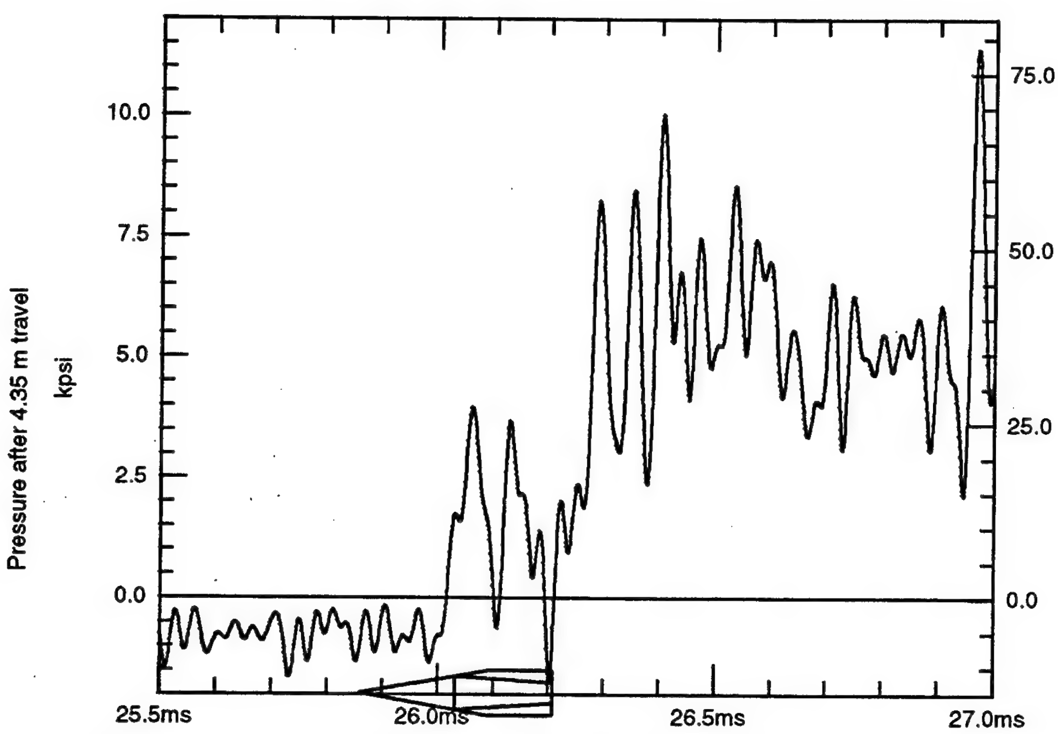

Figure 11. Ram combustion in a 120-mm accelerator after 4.35-m travel. Projectile is scaled to local velocity.

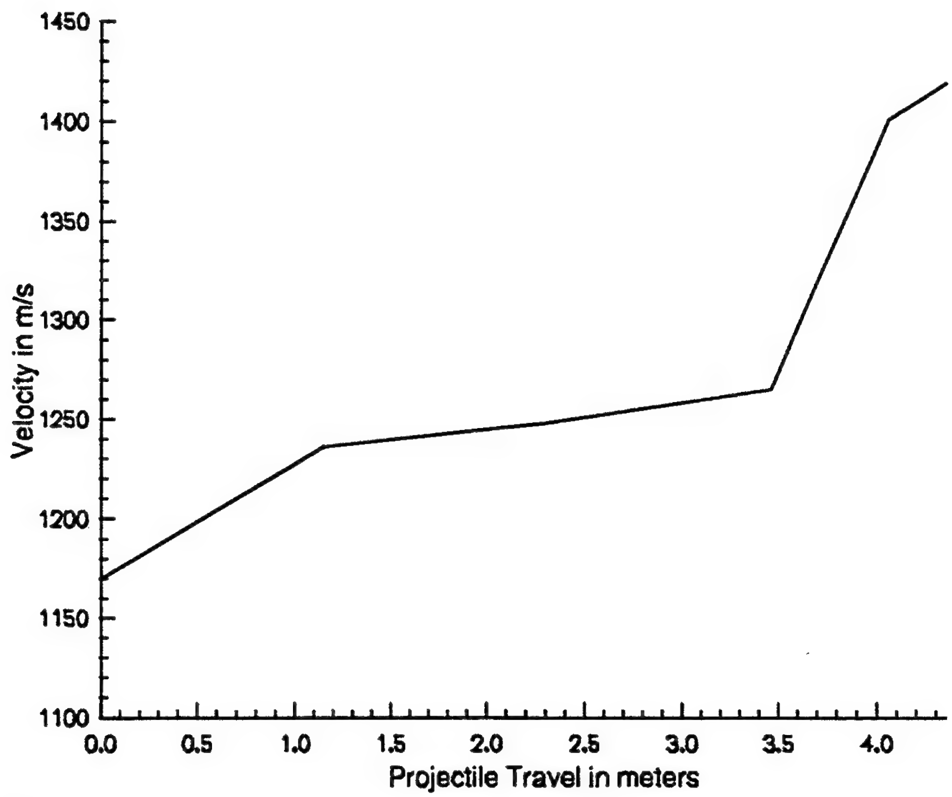

Figure 12. Plot of projectile velocity vs. projectile travel for 120-mm ram accelerator (round 15).

propellant mixing by partial pressure is a viable alternative to more complex mixing schemes for obtaining homogeneous propellant mixtures in ram accelerators. The usefulness of inert firings to analyze obturator performance and shock/pressure structure in ram accelerators has been further validated. Finally, the scaling potential of ram acceleration has been firmly established with the first successful test at 120-mm caliber.

6. FUTURE

Future plans for the HIRAM experimental program will include parametric evaluation of propellant fill pressure effects, examination of the process through optically clear tube sections, instrumented projectiles for base pressure and acceleration measurements, and application of other advanced diagnostic techniques for inbore flow measurements. In addition, the accelerator length will be increased to explore higher velocity/Mach number regimes.

INTENTIONALLY LEFT BLANK.

7. REFERENCES

Bruckner, A. P., E. A. Burnham, C. Knowlen, and A. Hertzberg. "Initiation of Combustion in the Thermally Choked Ram Accelerator." Proceedings of the 18th International Symposium on Shock Waves, Sendai, Japan, 21–26 July 1991.

Giraud, M., J. F. Legendre, G. Simon, and L. Catoire. "RAM Accelerator in 90 mm Caliber, First Results Concerning the Scale Effect in the Thermally Choked Propulsion Mode." Proceedings of the 13th International Symposium on Ballistics, Stockholm, Sweden, 1–3 June 1992.

Giraud, M., J. F. Legendre, and G. Simon. "RAM Accelerator Studies in 90 mm Caliber." 43rd Meeting of the Aeroballistic Range Association, Columbus, OH, 28 September–2 October 1992.

Hertzberg, A., A. P. Bruckner, and D. W. Bogdanoff. "Ram Accelerator: A New Chemical Method for Accelerating Projectiles to Ultrahigh Velocities." AIAA Journal, vol. 26, pp. 195–203, 1988.

Knowlen, C., A. P. Bruckner, and A. Hertzberg. "Internal Ballistics of the Ram Accelerator." Proceedings of the 13th International Symposium on Ballistics, Stockholm, Sweden, 1–3 June 1992.

Knowlen, C., J. B. Higgins, E. A. Burnham, and A. T. Mattick. "Diagnostic Techniques for the Ram Accelerator Phenomena." 43rd Meeting of the Aeroballistic Range Association, Columbus, OH, 28 September–2 October 1992.

Kruczynski, D. L. "Analysis of Ram Acceleration for High Velocity Applications." AIAA Paper 91-2488, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference, Sacramento, CA, 24–26 June 1991a.

Kruczynski, D. L. "Requirements, Design, Construction, and Testing of a 120-mm Inbore Ram Accelerator." 28th JANNAF Combustion Meeting, CPIA publication 573, vol. 1, October 1991b.

Kruczynski, D. L., and M. J. Nusca. "Experimental and Computational Investigation of Scaling Phenomena in a Large Caliber Ram Accelerator." AIAA paper 92-3245, AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville, TN, 6–8 July 1992.

Kruczynski, D. L. Private communication with Dr. Marc Giraud, ISL, 5 October 1992.

Nusca, M. J. "Numerical Simulation of Reacting Flow in a Thermally Choked Ram Accelerator Projectile Launch System." AIAA paper 91-2490, AIAA/SAE/ASME/ASEE 27th Joint Propulsion Conference, Sacramento, CA, 24–26 June 1991a.

Nusca, M. J. "Navier-Stokes Simulation of Fluid Dynamic and Combustion Phenomena in the RAM Accelerator." 28th JANNAF Combustion Meeting, CPIA publication 573, vol. 1, October 1991b.

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFO CTR ATTN DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CS AL TA 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB ATTN AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	ABERDEEN PROVING GROUND
2	DIR USARL ATTN AMSRL CI LP (305)

NO. OF COPIES	ORGANIZATION
2	HQDA ATTN SARD TT DR F MILTON MR J APPEL WASHINGTON DC 20310-0103
1	HEADQUARTERS USA MATERIAL CMD ATTN AMCICP AD M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	USA BALLISTIC MIS DEFNS SYS CMD ADV TECH CTR PO BOX 1500 HUNTSVILLE AL 35807-3801
2	COMMANDER USA ARDEC ATTN SMCAR CCH V C MANDALA E FENNELL PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR AEE J LANNON PICATINNY ARSENAL NJ 07806-5000
7	COMMANDER USA ARDEC ATTN SMCAR AEE B D DOWNS S EINSTEIN S WESTLEY S BERNSTEIN J RUTKOWSKI B BRODMAN P HUI PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR AEE WW M MEZGER PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER USA ARDEC ATTN SMCAR FSA F LTC R RIDDLE PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR FS T GORA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA ARDEC ATTN SMCAR FS DH J FENECK PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER USA ARDEC ATTN SMCAR FSN N K CHUNG A BAHIA R LEE PICATINNY ARSENAL NJ 07806-5000
2	DIRECTOR BENET WEAPONS LABORATORIES ATTN SMCAR CCB RA G OHARA G PFLEGL WATERVLIET NY 12189-4050
1	DIRECTOR BENET WEAPONS LABORATORIES ATTN SMCAR CCB S S HEISER WATERVLIET NY 12189-4050
2	COMMANDER USA RSRCH OFC ATTN TECH LIB D MANN PO BOX 12211 RESEARCH TRIANGLE PARK NC 227709-2211

NO. OF COPIES	ORGANIZATION
1	COMMANDER USA CECOM ATTN ASQNC ELC IS L R MYER CTR R&D TECH LIB FORT MONMOUTH NJ 07703-5301
1	COMMANDER USA BELVOIR R&D CTR ATTN STRBE WC FORT BELVOIR VA 22060-5006
1	COMMANDER USA FSTC ATTN AMXST MC 3 220 SEVENTH ST NE CHARLOTTESVILLE VA 22901-5396
1	USA RSRCH OFC (UK) PSC 802 BOX 15 DR ROY E REICHENBACH APO AE 09499-1500
2	COMMANDER NAVAL SEA SYS CMD ATTN SEA 62R SEA 64 WASHINGTON DC 20362-5101
1	COMMANDER NAVAL AIR SYS CMD ATTN AIR 954 TECH LIB WASHINGTON DC 20360
1	COMMANDER NAVAL RSRCH LAB ATTN TECH LIB WASHINGTON DC 20375-5000
4	COMMANDER NAVAL RSRCH LAB ATTN CODE 6410 K KAILASANATE C LI J BORIS E ORAN WASHINGTON DC 20375-5000

NO. OF COPIES	ORGANIZATION
1	OFFICE OF NAVAL RSRCH ATTN CODE 473 R MILLER 800 N QUINCY ST ARLINGTON VA 22217-9999
1	OFFICE OF NAVAL TECHNOLOGY ATTN ONT 213 D SIEGEL 800 N QUINCY ST ARLINGTON VA 22217-5000
7	COMMANDER NSWC ATTN T SMITH K RICE S MITCHELL S PETERS J CONSAGA C GOTZMER TECH LIB INDIAN HEAD MD 20640-5000
1	COMMANDER NSWC ATTN CODE G30 GUNS & MUNITIONS DIV DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE G32 GUNS SYSTEMS DIV DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE G33 T DORAN DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE E23 TECH LIB DAHLGREN VA 22448-5000
1	COMMANDER NSWC ATTN CODE C23 G GRAFF DAHLGREN VA 22448-5000

NO. OF COPIES	ORGANIZATION
2	COMMANDER NAWC ATTN CODE 388 C PRICE T BOGGS CHINA LAKE CA 93555-6001
2	COMMANDER NAWC ATTN CODE 3895 T PARR R DERR CHINA LAKE CA 93555-6001
1	COMMANDER NAWC ATTN INFO SCI DIV CHINA LAKE CA 93555-6001
1	COMMANDING OFFICER ATTN CODE 5B331 TECH LIB NAVAL UNDERWATER SYS CTR NEWPORT RI 02840
1	AFOSR NA ATTN J TISHKOFF BOLLING AFB DC 20332-6448
1	OLAC PL TSTL ATTN D SHIPLETT EDWARDS AFB CA 93523-5000
3	OLAC PL RK ATTN J LEVINE L QUINN T EDWARDS 5 POLLUX DR EDWARDS AFB CA 93524-7048
1	WL MNAA ATTN B SIMPSON EGLIN AFB FL 32542-5434
1	WL MNME ENERGETIC MATERIALS BR 2306 PERIMETER RD STE 9 EGLIN AFB FL 32542-5910

NO. OF COPIES	ORGANIZATION
1	WL MNSH ATTN G ABATE EGLIN AFB FL 32542-5434
1	WL POPS ATTN B SEKAR BLDG 18 1950 FIFTH ST WRIGHT PATTERSON AFB OH 45433
2	NASA LANGLEY RSRCH CTR ATTN MS 408 W SCALLION D WITCOFSKI HAMPTON VA 23605
1	ELORET ATTN D BOGDANOFF MS 230 2 NASA AMES RSRCH CTR MOFFETT FIELD CA 94035-1000
1	CENTRAL INTELLIGENCE AGENCY OFC OF INFORMATION RESOURCES ROOM GA 07 HQS WASHINGTON DC 20505
1	CENTRAL INTELLIGENCE AGENCY ATTN J BACKOFEN NHB ROOM 5N01 WASHINGTON DC 20505
1	SDIO TNI ATTN L CAVENY PENTAGON WASHINGTON DC 20301-7100
1	SDIO DA ATTN E GERRY PENTAGON WASHINGTON DC 21301-7100
2	HQ DNA ATTN D LEWIS A FAHEY 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398

NO. OF COPIES	ORGANIZATION
1	DIRECTOR SANDIA NATL LABS ATTN M BAER ENERGETIC MATL & FLUID MECH DEPT 1512 PO BOX 5800 ALBUQUERQUE NM 87185
1	DIRECTOR SANDIA NATL LABS ATTN R CARLING COMBUSTION RSRCH FACILITY LIVERMORE CA 94551-0469
1	DIRECTOR SANDIA NATL LABS ATTN 8741 G BENEDETTI PO BOX 969 LIVERMORE CA 94551-0969
2	DIRECTOR LLNL ATTN L355 A BUCKINGHAM M FINGER PO BOX 808 LIVERMORE CA 94550-0622
1	DIRECTOR LOS ALAMOS SCIENTIFIC LAB ATTN T3 D BUTLER PO BOX 1663 LOS ALAMOS NM 87544
1	DIRECTOR LOS ALAMOS SCIENTIFIC LAB ATTN M DIVISION B CRAIG PO BOX 1663 LOS ALAMOS NM 87544
1	UNIV OF TEXAS AT AUSTIN INST FOR ADV TECH ATTN T KIEHNE 4030 2 W BRAKER LN AUSTIN TX 78759-5329

NO. OF COPIES	ORGANIZATION
2	CPIA JHU ATTN H HOFFMAN T CHRISTIAN 10630 LITTLE PATUXENT PKWY STE 202 COLUMBIA MD 21044-3200
1	CA INST OF TECH ATTN L STRAND MS 125 224 JET PROPULSION LAB 4800 OAK GROVE DR PASADENA CA 91109
1	CA INST OF TECH ATTN F CULICK 204 KARMAN LAB MS 301 46 1201 E CALIFORNIA ST PASADENA CA 91109
2	GA INST OF TECH SCHOOL OF AEROSPACE ENGRG ATTN B ZIM E PRICE ATLANTA GA 30332
2	UNIV OF ILLINOIS DEPT OF MECH IND ENGRG ATTN H KRIER R BEDDINI 144 MEB 1206 N GREEN ST URBANA IL 61801-2978
1	UNIV OF MASSACHUSETTS DEPT OF MECHANICAL ENGRG ATTN K JAKUS AMHERST MA 01002-0014
1	UNIV OF MINNESOTA ATTN E FLETCHER DEPT OF MECHANICAL ENGRG MINNEAPOLIS MN 55414-3368
3	PENNSYLVANIA STATE UNIV DEPT OF MECHANICAL ENGRG ATTN V YANG K KUO C MERKLE UNIVERSITY PARK PA 16802-7501

NO. OF COPIES	ORGANIZATION
1	RENSSELAER POLYTECHNIC INST DEPT OF MATHEMATICS TROY NY 12181
1	STEVENS INST OF TECH DAVIDSON LABORATORY ATTN R MCALEVY III CASTLE POINT STATION HOBOKEN NJ 07030-5907
1	RUTGERS UNIVERSITY DEPT OF MECH & AEROSPACE ENGRG ATTN S TEMKIN UNIVERSITY HEIGHTS CAMPUS NEW BRUNSWICK NJ 08903
1	UNIV OF UTAH DEPT OF CHEMICAL ENGRG ATTN A BAER SALT LAKE CITY UT 84112-1194
1	WASHINGTON STATE UNIV DEPT OF MECHANICAL ENGRG ATTN C CROWE PULLMAN WA 99163-5201
1	STANFORD UNIVERSITY MECHANICAL ENGRNG DEPT ATTN R HANSON STANFORD CA 94305-3032
1	PURDUE UNIVERSITY SCHOOL OF AERO & ASTRO ATTN N MESSERSMITH 1282 GRISSOM HALL WEST LAFAYETTE IN 47907-1282
1	GENERAL APPLIED SCIENCES LAB ATTN J ERDOS 77 RAYNOR AVE RONKONKAMA NY 11779-6649
1	FMC CORPORATION NAVAL SYSTEMS DIVISION ATTN A GIOVANETTI 4800 E RIVER RD MINNEAPOLIS MN 55421

NO. OF COPIES	ORGANIZATION
4	MARTIN MARIETTA TACTICAL SYSTEM DEPT ATTN J MANDZY I MAGOON P JORDAN D COOK 100 PLASTICS AVE PITTSFIELD MA 01201-3698
2	HERCULES INC ALLEGHENY BALLISTICS LAB ATTN W WALKUP T FARABAUGH PO BOX 210 ROCKET CENTER WV 26726
2	OLIN ORDNANCE ATTN A GONZALEZ D WORTHINGTON PO BOX 222 ST MARKS FL 32355-0222
1	OLIN ORDNANCE ATTN H MCELROY 10101 NINTH ST N ST PETERSBURG FL 33716
2	PRINCETON COMBUSTION RSRCH LABS INC ATTN N MER N A MESSINA PRINCETON CORPORATE PLAZA 11 DEERPARK DR BLDG IV STE 119 MONMOUTH JUNCTION NJ 08852
1	SAIC ATTN M PALMER 2109 AIR PARK RD ALBUQUERQUE NM 87106
1	SOUTHWEST RSRCH INSTITUTE ATTN J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
1	SVERDRUP TECHNOLOGY INC ATTN DR J DEUR 2001 AEROSPACE PKWY BROOK PARK OH 44142

NO. OF COPIES	ORGANIZATION
2	VERITAY TECHNOLOGY INC ATTN E FISHER R TALLEY 4845 MILLERSPORT HWY EAST AMHERST NY 14501-0305
1	ADROIT SYSTEMS INC ATTN J HINKEY 411 108TH AVE NE STE 1080 BELLEVUE WA 98004
1	NASA ATTN CODE 5 11 B MCBRIDE CLEVELAND OH 44135-3191
2	UNIVERSITY OF WASHINGTON AERO & ENGERTICS RSRCH PRGM ATTN A BRUCKNER BOX 352250 SEATTLE WA 98195-2250
1	THE JOHNS HOPKINS UNIV APPLIED PHYSICS LABORATORY ATTN D VAN WIE LAUREL MD 20723
	ABERDEEN PROVING GROUND
1	COMMANDER USA ATC ATTN: STECS-LI R. HENDRICKSEN

NO. OF COPIES	ORGANIZATION
1	ERNST-MACH-INSTITUT ATTN: DR. R HEISER HAUPSTRASSE 18 WEIL AM RHEIM GERMANY
1	DEFENCE RESEARCH AGENCY, MILITARY DIVISION ATTN: C. WOODLEY RARDE FORT HALSTEAD SEVENOAKS KENT, TN14 7BP ENGLAND
1	DEFENCE RESEARCH AGENCY FLIGHT DYNAMIC SECTION ATTN: CASEY PHAN WX7e BLDG S 16 FORT HALSTEAD SEVENOAKS KENT TN 7BP ENGLAND
1	SCHOOL OF MECHANICAL, MATERIALS, AND CIVIL ENGINEERING ATTN: DR. BRYAN LAWTON ROYAL MILITARY COLLEGE OF SCIENCE SCHRIVANHAM, SWINDON, WILTSHIRE SN6 8LA ENGLAND
2	INSTITUT SAINT LOUIS ATTN: DR. MARC GIRAUD DR. GUNTHER SMEETS POSTFACH 1260 7858 WEAIL AM RHEIN 1 GERMANY
1	EXPLOSIVE ORDNANCE DIVISION ATTN: A. WILDEGGER-GAISSMAIER DEFENCE SCIENCE AND TECHNOLOGY ORGANIZATION P. O. BOX 1750 SALISBURY, SOUTH AUSTRALIA, 5108
1	ARMAMENTS DIVISION ATTN: DR. J. LAVIGNE DEFENCE RESEARCH ESTABLISHMENT VALCARTIER 2459, PIE XI BVLD., NORTH P. O. BOX 8800 COURCELETTE, QUEBEC G0A 1R0 CANADA
1	BALLISTIC TECHNOLOGIES ATTN: PAVEL KRYUKOV MOSCOW REGION B. O. 92 KALININGRAD, MOSCOW 141070 RUSSIA
1	TOHOKU UNIVERSITY INSTITUTE FOR FLUID SCIENCE ATTN: AKIHIRO SASOH 2-1-1 KATAHIRA, AOBA SENDAI, 980-77 JAPAN
1	HIROSHIMA UNIVERSITY DEPT OF MECHANICAL ENGINEERING ATTN: XINYU CHANG 1-4-1 KAGAMIYAMA HIGASHI-HIROSHIMA, 739 JAPAN

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1237 (Kruczynski) ____________ Date of Report November 1996 ______

2. Date Report Received ______________________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______________________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______________________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______________________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______________________________

CURRENT ADDRESS

____
Organization

____
Name

____
Street or P.O. Box No.

____
City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

____
Organization

____
Name

____
Street or P.O. Box No.

____
City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)

DEPARTMENT OF THE ARMY

OFFICIAL BUSINESS

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO 0001,APG,MD

POSTAGE WILL BE PAID BY ADDRESSEE

DIRECTOR
U S ARMY RESEARCH LABORATORY
ATTN AMSRL WT PA
ABERDEEN PROVING GROUND MD 21005-5066